Title

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Authors

Zhang, Teresa
Boyd, Sarah
Vijayaraghavan, Athulan
et al.

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Teresa W. Zhang, Sarah Boyd, Athulan Vijayaraghavan and David Dornfeld
Department of Mechanical Engineering
Consortium for Green Design and Manufacturing
University of California at Berkeley
134 Hesse Hall, Berkeley, CA 94720
{resa, sboyd, athulan, dornfeld}@berkeley.edu

Abstract— **This paper presents an overview of key nanoscale manufacturing technologies, and qualitatively examines their fundamental process requirements with respect to energy demand. The processes requirements are related to semiconductor manufacturing, where applicable, and gaps in our understanding of these processes on the production scale are identified as goals for the research community. Finally, the paper proposes a framework for the systematic analysis of energy use in nanoscale manufacturing processes.**

I. INTRODUCTION

Nanoscale manufacturing can be defined as the control and manipulation of materials to a precision of one to one hundred nanometers in at least one dimension [1]. As materials exhibit fundamentally different behavior in this scale, new products may be developed with improved performance characteristics. Efficient and scalable nanoscale manufacturing methods are required to harness the benefits of nanotechnology for broader use. As the use of nanoscale manufacturing increases, it becomes necessary to measure and manage the energy efficiency of these processes. Energy usage dictates both the environmental and the economic efficiency of manufacturing processes.

Nanoscale devices have demonstrated the potential to provide energy savings in their use phases [2], [3]. However, increased precision requirements drive up manufacturing costs, particularly those from energy use [4]. Hence, in order for nanoscale devices to be energy efficient across their entire life cycles, care should be taken in the selection of the manufacturing technology used. Moreover, monitoring energy use also leads to the identification of opportunities to improve the efficiency and productivity of the manufacturing method.

This paper reviews the major classes of nanoscale manufacturing methods and identifies the direct and indirect process requirements needed for their operation. With this background, it discusses a qualitative comparison of the process requirements and associated energy demands of the various methods. To promote the development of this emerging field, we suggest a roadmap for the comprehensive study of energy use in nanoscale manufacturing.

II. MANUFACTURING TECHNOLOGIES

Nanoscale manufacturing can be seen as an evolution of semiconductor manufacturing and faces many of the same energy issues, such as large direct process energy requirements, extreme part complexity, highly processed and purified material inputs, and vulnerability to contaminants. Additional considerations specific to certain nano-processing technologies include: low throughput, built-in metrology, and extreme temperature and vacuum requirements.

This section presents a discussion of various nanoscale manufacturing methods. Past work in this field includes [5] and [6], which discuss conventional versus next generation lithography (NGL) methods. Here, we categorize nanoscale manufacturing technologies by their basic constituent mechanisms, as these mechanisms drive energy use.

Nanoscale fabrication methods can be broadly characterized as top-down and bottom-up approaches. Top-down refers to subtractive methods, involving etching, machining or molding larger parts to a desired size, while bottom-up describes the formation of materials or devices additively from individual molecules or atoms. Each class of nanoscale manufacturing technologies are described briefly.

A. Top-Down Technologies

1) Lithography: Lithography encompasses a wide range of manufacturing processes that selectively employ beams of photons, electrons, or ions to modify the mechanical properties of a material or masking resist layer.

Lithography processes consists of 3 main steps: pattern generation, exposure, and feature development. Patterns are most often generated on a mask, which are used in the exposure step to create features one die at a time or one wafer at a time. Direct-write or maskless lithography is possible when the spot size, or beam diameter, is no larger than the feature size. Finally, the material is developed to expose the desired features, most commonly by chemical etching.

Photolithography or optical lithography uses light to harden or soften a polymer photoresist, which is then used as an etch mask. The Rayleigh resolution limit dictates that only extreme ultra violet (EUV) and some deep ultra violet (DUV) light have wavelengths short enough to produce features on the nanoscale [7]. EUV light, with wavelengths less than 31nm, requires specialized equipment as quartz lenses absorb rather than refract at this wavelength.

Many new experimental methods are aimed at surpassing the Rayleigh limit. The wavelength of light can be modified by the interference of multiple sources or by passing light through various mediums. Plasmonic imaging lithography (PIL), for example, uses the short wavelength of surface waves, or plasmons, to obtain 60nm resolution using a 365nm mercury lamp [8].

The resolution attainable by conventional photolithographic processes is rapidly increasing, in accordance with the International Technology Roadmap for Semiconductors (ITRS), and gate length after etching is projected to reach 20nm by 2009, from 32nm today [9].

*X-ray lithography (*XRL*)* offers greater resolution than photolithography using wavelengths ranging from 0.03nm to 3nm. X-rays can penetrate many common mask materials and even specialized mask materials often require cooling during operation. LGA (from Lithographi Glvanoformung Abformnug in German) is an x-ray lithography process capable of high aspect ratios using electroplating. Features down to 15nm are possible using XRL.

Electron beam (e-beam) *lithography* is a direct-write technology. Its resolution is not limited by the diffraction limit of light, but by beam width and electron scattering. Scanning electron microscopes (SEM) are the equipment most commonly used in e-beam lithography. E-beam lithography is a very mature technology as it is used to create lithography masks used in conventional semiconductor manufacturing. Feature dimensions down to 10nm are obtainable using this technology.

Ion beam lithography or focused ion beam (FIB) lithography is capable of directly removing material, combining pattern generation, exposure and feature development into a single process step. Ion beams are formed by charging a substance such as helium, oxygen, boron and phosphorus. Because the heavier ions scatter less than electrons, ion beam lithography is capable of the greatest resolution of all processes in this category.

2) Imprint Technologies: Nanoimprint lithography (NIL) is also referred to as nanoembossing lithography or soft lithography. A layer of soft thermoplastic, molten silicon or liquid photoresist is pressed or poured onto a mold, and is subsequently hardened with heat or ultraviolet light [10], [11], [12]. Anisotropic reactive ion etching is often then required to remove all but the desired features. The features may be left as-is or can be lifted-off once another material is deposited in the pattern gaps. Molds are often used between 1 and 30 times as degradation appears over time. Imprint lithography is capable of resolutions less than 5nm and has potential for high throughput manufacturing.

3) Single Point Operations: Single point operations refers to material removal using scanning probe microscopy, most commonly by atomic force microscopy (AFM) or scanning tunnel microscopy (STM). These are distinguished from other top-down approaches as the material is removed in a serial atom-by-atom fashion.

Scanning probe microscopes can be employed with voltage pulse, chemical vapor deposition (CVD), local electrodeposition or dip-pen nanolithography (DPN) techniques. These processes require extreme pressure and temperature conditions. This approach can be exceedingly time intensive, though it is capable of atomic scale resolution.

B. Bottom-Up Technologies

*1) Vapor Processes: Chemical vapor deposition (*CVD*)* uses the deposition of reactive gas on the surface of a substrate in bottom-up as well as top-down manufacturing. Nanowires, composite nanowires, and carbon nanotubes (CNTs) may be produced using CVD, often in the presence of a catalyst. For example, CNTs are produced by CVD from a hydrocarbon source material at temperatures between 600° C and 1000° C in vacuum or inert media with a transition metal catalyst [13]. Gold nanowires may be formed by depositing gold vapor onto combed DNA in a process termed templated self-assembly [5].

*Vapor-liquid-solid (*VLS*) processes* involve the introduction of a gaseous feed material to a liquid catalyst in order to form a crystalline solid. VLS occurs at atmospheric pressure and is used to form nanowires, which are ultra fine lines composed of a single material.

The process of VLS can be explained simply as a CVD process with nanoparticles of catalyst on the substrate. Nanowires of Si, Ge, GaAs, GaP, InP, InAs, ZnS, ZnSe, CdS, CdSe, ZnO, MgO and SiO_2, as well as single and multi-wall carbon nanotubes (SWNT, MWNT) are products of VLS. Nanoparticles of catalyst on a substrate are heated in a furnace chamber where a source vapor is introduced to produce and continuously deposit a eutectic alloy. The energy demands for production of each type of nanowire thereby vary with the eutectic temperature of the alloy and growth rate of the wire.

Carbon nanotubes may also be formed by VLS with the use of a catalyst. More widely pursued methods of CNT formation include sublimation of solid graphite through laser ablation, electric arc discharge or solar energy. In laser ablation, sublimation occurs using a laser in a high temperature (1200° C) furnace under vacuum in inert media (usually helium), sometimes in the presence of a catalyst. CNTs are also formed by electric arc in similar conditions, always in the presence of a catalyst. Solar furnaces reach temperatures in the range of 3700° C with focused sunlight, where a solid graphite source with a catalyst under vacuum sublimates and deposits on the walls of the chamber [13].

In *Molecular beam epitaxy* (MBE), flows of ultra-pure gas at high temperature and ultra high vacuum (UHV) are directed onto a single crystal substrate. These flows are used to form quantum dots or wires, from crystals 10 to 10^5 atoms thick [13].

2) Liquid-Only Processes: Self-assembled monolayers may be formed by the Langmuir-Blodgett method, wherein a solid substrate is dipped into a liquid covered by a thin layer of surfactant, or by spin-casting. These films may be further processed using e-beam lithography or other top-down techniques.

3) Plasma/Ion Processes: Single ion implantation uses a low dose, low energy beam to implant ions into a crystal surface in ultra high vacuum and may be used to form quantum dots.

Plasma enhanced CVD (PECVD) employs the same mechanism as CVD but, by using a charged gas, allows films to form at lower temperatures.

4) Imprint Processes: Nanocontact printing (nCP) or nanotransfer printing (nTP) are related to top-down imprint processes. Here, a desired material is evaporated onto a stamp or mold and then transferred to a planar substrate [14], [15]. The resolution of nCP can be as high as 40nm.

5) Single Point Operations: The mechanism of bottom-up scanning probe microscopy are closely related to that of scanning probe microscopy material removal. Scanning probe microscopy was most famously used to form the letters "IBM" using 35 xenon atoms in 1991.

The resolution of scanning probe microscopy is limited by the interaction volume between the probe and the sample, but nevertheless can be considered the most precise of all nanoscale manufacturing technologies. However, the process can be extremely unreliable and low throughput.

III. PROCESS ENERGY REQUIREMENTS

Each of the manufacturing technologies discussed have specific requirements for operation. These requirements are broken down into those that can be measured per unit product versus those that are allocated over a production facility. We call these direct and indirect process requirements, respectively. The major process requirements along with their energy demands are discussed in this section.

Since many of the manufacturing technologies are still in their developmental stages, it is difficult to obtain data on energy consumption. There are, however, well documented studies of mature semiconductor manufacturing technologies [16], [17], [18]. Due to similarities between semiconductor and nanoscale manufacturing technologies, it is appropriate to use some of this data as lower-bound estimates for energy use in nanoscale manufacturing. However, there are numerous gaps in the available knowledge, which are also identified below. These areas should be the focus of the nanotechnology life cycle analysis community.

A. Direct Requirements

Direct requirements are those applied directly at the process or point-of-use (POU). Energy use can be measured directly from the experimental equipment, but must be viewed in light of potentially increased production-scale efficiency. It should also be noted that we are interested in the energy supplied to the process equipment rather than the energy used in the process or the primary energy generated.

1) Pressure Control: Pumps are used to maintain the vacuum conditions required for many fabrication methods. Vacuum conditions are crucial for minimizing contaminants in the parts being produced, as well as to extend the mean free path, or anisotropy, of materials being deposited.

Pressures down to 10^{-3} torr can be attained with roughing, or mechanical, pumps alone. Pressures lower than this threshold require a diffusion or turbo pump in series with the roughing pump. Energy use in pressure control is therefore dependent on the pressures required for each process. The basic machine requirements differ very little from those of semiconductor manufacturing. However, as the throughput of many nanoscale processes is relatively low, the machine must operate over a longer working cycle. Hence, when compared to semiconductor manufacturing, the energy use from pressure control will scale inversely with the throughput of nanoscale operations.

2) Temperature Control: Specific high or low chamber temperatures are required for many nanoscale processes. Furnace temperatures, ranging from 400° C to 1400° C are necessary for oxidation, thin film deposition, diffusion, annealing, and sintering processes, while oven temperatures around 100° C are used to dry and harden photoresists and other masking substrates. Cold temperatures are required for processes that require great purity, including scanning probe microscopy, plasma processes, etching, and ion implantation. These processes can be successful only in the absence of uncontrolled kinetic energy sources; hence both vacuum and low temperature conditions are required. While hot and cold temperatures are attained through the same mechanisms as in semiconductor manufacturing, the energy expenditures will again scale with throughput.

3) Photon Generation: Ultraviolet light is used to soften or harden photoresist, the resolution of which is inversely dependent on the wavelength of the light source. However, the shorter the wavelength, the more energy is transmitted in the photon, as given by:

$$E = h \times \frac{c}{\lambda} \tag{1}$$

where h is planck's constant, c is the speed of light and λ is the wavelength. An average arc lamp bulb may dissipate 500-1000W. Since EUV wavelengths are an order of magnitude shorter than that of optical light sources, they are roughly an order of magnitude more energy intensive.

4) Plasma/Ion Generation: Plasma sources are used to etch and deposit material, and to implant ions into a substrate. Plasma generation and control is energy intensive and can consume from 50W to 50kW depending on the application. Because lower beam energies are used for single or small scale ion implantation, the energy requirements of nanoscale processes associated with this requirement will be lower with respect to those used in semiconductor manufacturing.

5) Precision Metrology and Mechanics: While throughput and process capability are still relatively low, part by part inspection is often necessary. This may rely on the same scanning probe microscopy tools and repeated trials used in feature creation. Table 1 lists the various types of metrology equipment required at different resolution scales.

More work is required in characterizing both the reliability and energy use of high precision equipment used in metrology and manufacturing itself. The study of the metrology requirements for a production system, as a function of feature size and production scale, is another priority.

B. Indirect Requirements

Facilities provide a layer of "protection" for the manufacturing processes. In experimental environments, appropriate

Resolution	Sample Metrology Tools
100nm	Laser measuring instruments, optical fibers, Talysurfs, Talyronds
10nm	High precision laser measuring instruments (Doppler, multi-reflection), Talysteps
1nm	Scanning electron microscopes, transmission electron microscopes, electron diffraction equipment, ion analyzers
0.3nm	X-ray micro analyzers, Auger analysers, ESCAR

TABLE I

METROLOGY INSTRUMENTS FOR FEATURES 0.3NM TO 100NM [4]

facilities may not yet be available. However, at production scales, it becomes critical to maintain tightly controlled conditions outside of process chambers. The processes inherit the purity and ambient conditions of the facilities and hence it is essential to maintain the facilities at these baseline conditions. This not only takes the load off of direct requirements, but reduces the risk of defects due to contamination.

Numerous materials must be continuously supplied to the process chamber, including clean room air, ultra pure water, and process cooling water. All of these must be recaptured to be conditioned and re-circulated or treated and released. In a modern-day semiconductor fabrication facility, a large fraction of energy use goes toward facilities scale support processes.

1) Purification: Ultrapure air, water and chemicals are required for all nanoscale manufacturing processes. Clean room recirculating fans are necessary for removing contaminants from the work environment air. Makeup air (MUA) is also used to pressurize the work area, keeping contaminants out. Ultra pure or deionized(DI) water is used in numerous cleaning steps. A ever-widening range of highly purified chemicals are used in both semiconductor and nanoscale manufacturing.

The highest available classes of clean room air are necessary components of both nanoscale manufacturing and semiconductor manufacturing, and the energy use associated with both are comparable, though again dependent on throughput.

One issue particularly pertinent to nanoscale manufacturing is how to clean without damaging features. Deionized water may be used differently in nanoscale manufacturing than in semiconductor manufacturing. This is an area in need of further study.

While some consumables span the gap from semiconductor manufacturing to nanoscale manufacturing, many others are being developed solely for the latter. On-site chemical purification is a major factor in energy use that will require extensive and continuous study as the field progresses. This is distinct from the embedded energy in process consumables, which will be another priority for the research community.

2) Temperature Control: Process cooling water (PCW) must be continually circulated to maintain desired temperatures. Process cooling water consumption for nanoscale manufacturing is similar to that of semiconductor manufacturing, scaling with process heat generation and throughput.

3) Abatement: Harmful or regulated chemicals are treated in two steps: once at the point of use (POU) and again at the facilities scale. Because both steps occur outside of the actual processes, they are considered within facilities requirements.

POU abatement focuses on the removal or separation of perfluorocompounds (PFCs) by burn and scrub, plasma treatment and scrub, or filtration respectively [19]. Facilities abatement involves a wider range of emissions than POU abatement. Acid waste neutralization, volatile organic compound (VOC) combustion, ammonia neutralization, fluorinated waste water treatment all occur in secondary abatement.

The species of chemicals and degree to which they are used and subsequently abated in nanoscale manufacturing is a major area of future work. The qualities and associated energy consumption of process outputs will be a priority consideration for any comprehensive study of nanoscale manufacturing.

IV. DISCUSSION

Given these energy intensive process requirements, let us take a look at the relative demands for them across the manufacturing technology classes. The total energy consumption of a method is driven by the extent to which its process requirements are used.

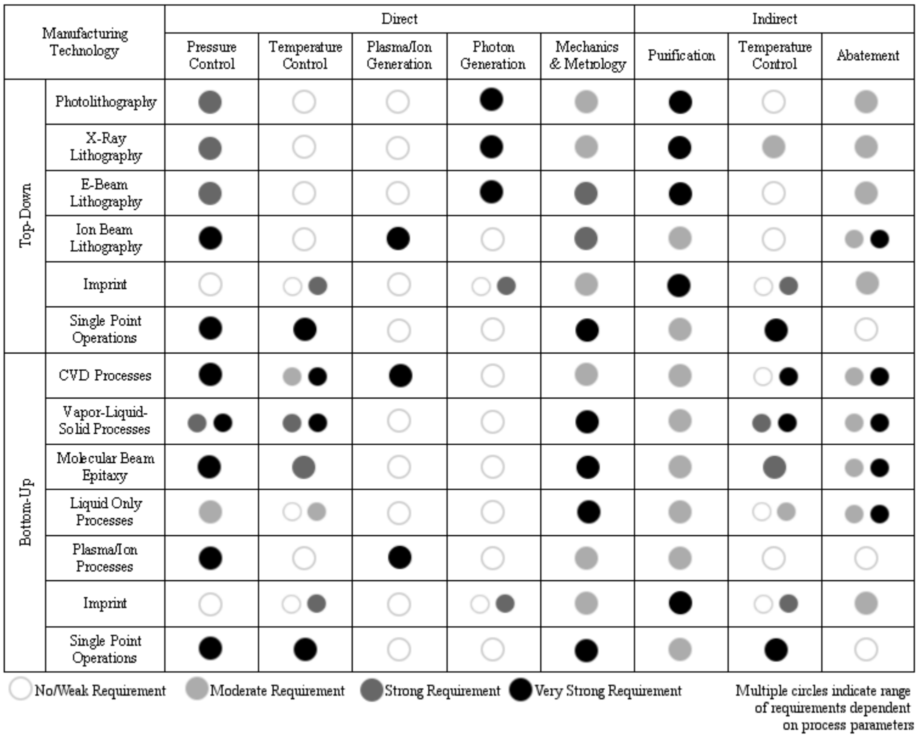
A qualitative assessment of process requirements is presented for each manufacturing technology class in Table II. In some cases, the process requirements are dependent on the material or process parameters used in manufacturing. For example, imprint lithography employs either heat or UV curing. This distinction affects relative demands of the process for photon generation, and direct and indirect temperature control. Abatement for ion beam lithography is chemistry dependent and may emit heavy metals. CVD abatement is process dependent and its emissions may contain perfluorocarbons or hazardous air pollutants. VLS processes occurs under a wide range of temperatures (from 1200° C for laser ablation to 3700° C for solar furnace CNT formation), so the degree of temperature control needed is process dependent.

From Table II, we can see that top-down and bottom-up processes with similar mechanisms have similar process requirements, and are therefore likely to have similar energy demands. If the process dependent scores are averaged for a manufacturing class, we find that imprint and plasma/ion processes have the least requirements while single point operations, CVD, VLS and MBE have the most requirements.

If we likewise average all the scores for top-down versus bottom-up manufacturing technologies, assigning values from zero for “no/weak requirement” to three for “very strong requirement”, we find that top-down processes score an average of 1.3 while bottom-up processes score an average of 1.4. This difference is marginal but suggests a hypothesis, that bottom-up manufacturing processes are more energy intensive than top-down processes, to explore in future work.

V. FUTURE WORK

The discussion section presents the basic elements of a systematic energy analysis for nanoscale manufacturing methods. Because the energy use per area depends on the precision and throughput of each process, process requirements serve



Manufacturing Technology		Direct					Indirect		
		Pressure Control	Temperature Control	Plasma/Ion Generation	Photon Generation	Mechanics & Metrology	Purification	Temperature Control	Abatement
Top-Down	Photolithography	◕	○	○	●	◔	●	○	◔
	X-Ray Lithography	◕	○	○	●	◔	●	◔	◔
	E-Beam Lithography	◕	○	○	●	◕	●	○	◔
	Ion Beam Lithography	●	○	●	○	◕	◔	○	◔ ●
	Imprint	○	○ ◕	○	○ ◕	◔	●	○ ◕	◔
	Single Point Operations	●	●	○	○	●	◔	●	○
Bottom-Up	CVD Processes	●	◔ ●	●	○	◔	◔	○ ●	◔ ●
	Vapor-Liquid-Solid Processes	◕ ●	◕ ●	○	○	●	◔	◕ ●	◔ ●
	Molecular Beam Epitaxy	●	◕	○	○	●	◔	◕	◔ ●
	Liquid Only Processes	◔	○ ◔	○	○	●	◔	○ ◔	◔ ●
	Plasma/Ion Processes	●	○	●	○	◔	◔	○	○
	Imprint	○	○ ◕	○	○ ◕	◔	●	○ ◕	◔
	Single Point Operations	●	●	○	○	●	◔	●	○

○ No/Weak Requirement ◔ Moderate Requirement ◕ Strong Requirement ● Very Strong Requirement

Multiple circles indicate range of requirements dependent on process parameters

TABLE II

PROCESS REQUIREMENTS FOR MANUFACTURING TECHNOLOGY CLASSES

as a proxy for actual energy use. A framework for a detailed, quantitative study of energy requirements for nanoscale manufacturing is proposed as follows:

- Develop a comprehensive set of requirements for all manufacturing technology class class including major consumables and process equipment
- Assess the range of precision attainable through each manufacturing method
- Estimate throughput for each technology class at various levels of precision based on industry projections and trends
- Quantify energy use associated with each process requirement, as a function of precision for each of the process classes
- Quantify energy embedded in materials and equipment using a combination of processed based and economic input-output life cycle assessment (EIO-LCA) energy data
- Identify scaling factors in energy demand as functions of resolution for each method, and compare extrapolated results with currently available data from the semiconductor industry

Using this model, a rigorous understanding of the energy consumption in nanoscale fabrication methods can be achieved. This framework can also be integrated into a broader lifecycle analysis of nanoscale manufacturing. Future work by the authors will involve developing the model as outlined in the framework.

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